JAMES WATT
(1736–1819)

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Abstract. It is generally accepted that the birth of James Watt was destined to bring about a revolution in the utilization of power. Watt, see Fig. 1, is regarded by many to be the progenitor of the science of thermodynamics. He was not only the inventor of the separate condenser and many other parts of the steam engine, but he was the first to study the steam engine scientifically. He also made distinguished contributions to the development of workshop practice. His scientific examination of heat losses in engines led him to recognition of the influence of latent heat on steam engine economy. Watt was at one and the same time a scientist, an inventor, and a producer. He put numbers to the concept of horsepower and is credited with inventing the centrifugal governor for automatic control of the speed of the steam engine, a rotary motion device for the steam engine, a pressure gauge, a smoke-consuming furnace, and a letter-copying device based on the link transfer process. Watt also invented an approximate straight-line mechanism for his famous double-acting steam engine, thereby creating a whole new family of linkages. This brief article will focus on Watt as the inventor of parallel motion, the basis of many machines. It is interesting to note that at the age of 72, he wrote to his son [1]: "Though I am not over-anxious after fame, yet I am more proud of the parallel motion than of any other mechanical invention I have ever made." Watt was rightfully proud of the parallel motion four-bar linkage. This mechanical invention is believed to be the beginning of an ordered and an advanced synthetic process [2].

Biographical Notes

James Watt was born on the 19th of January 1736, the fourth son to James and Agnes Watt. He was born near the port of Greenock, on the southern bank of the River Clyde, not far from where the Clyde turns south into the Firth and about twenty-five miles west of the City of Glasgow. From a young age Watt showed signs of the chronic ill-health that was going to torment him through the greater part of his life. His mother was devoted to him, and, rather than

M. Ceccarelli (ed.), Distinguished Figures in Mechanism and Machine Science, 337–369.

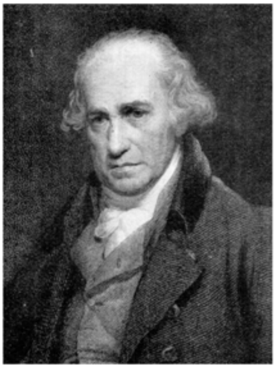

Fig. 1. James Watt in later years.

send him to a school where he might not be properly looked after, she kept him for a time under her own care at home and gave him his first lessons. By the time he was let out of the family circle into a wider world, his individuality and originality were already well developed, and he never showed any tendency to adapt himself to the type that was most admired by his schoolfellows. He went his own way and took the consequences, and they must have been severe. Watt was slow and awkward, and fell below the ordinary standard demanded by the common routine of school lessons. In fact, Watt was thought rather dull at his lessons. However, when he adapted to his new surroundings and found work that was congenial to him, his genius peeped through the veil of his childishness. His abilities began to appear when, at the age of about fourteen, he was put into a mathematical class, and made rapid progress. For a more detailed account of Watt's schooldays, the reader is referred to [3–5].

In 1753, when Watt was seventeen, his mother died. It was probably his mother's devotion to him that had kept Watt so long at home when other boys of his age were away earning their living. It is believed her death broke up the family life at Greenock. In June of the following year he went to Glasgow to learn the craft of a mathematical instrument maker. It was a profession closely allied to those of his father and his grandfather, and it gave more scope to his mechanical dexterity than he would have obtained by following either of their trades. The prospects, too, were good. It was described, at this date, as a "very ingenious and profitable business," and was by no means overstocked with labor.

When Watt arrived in Glasgow, however, he found there was no one who could teach him. He spent a year there, working under a nondescript mechanic who called himself an "optician," until he attracted the attention of Dr. Dick, Professor of Natural Philosophy at the University of Glasgow. Dick realized that here was a first-class talent going to waste, and advised him to go to London and obtain the best training that was available. Watt asked the permission of his father to go, and it was granted. It was a momentous decision, for this was surely the first time in the history of the Watt family that a member had proposed to cross the border from Scotland to England. Also, London was a long way from Glasgow when traveling on horseback. In addition, there was the expense to consider. Apparently Watt's father had either overreached himself in his speculations or had suffered losses at sea; for, although he had once been quite well-to-do, he was now obliged to leave his son to make his own way in the world, giving him only the most meager of allowances while he was obtaining his training. In spite of all these difficulties the adventure was accepted, and on June 7th, 1755, Watt set off for London, with a letter of introduction from Dr. Dick.

It took Watt approximately twelve days to reach London, and immediately he encountered some difficulties. The city was still clinging to ancient customs and privileges, chief among which was the right to keep all of its trade in the hands of the native-born townsmen, and to forbid anyone from another town to settle down within the city walls to earn a living. The time was long past when any town could preserve this monopoly intact, or indeed wanted to, but the right remained in theory, and could be used discreetly to remove undesirables. The vagrant, who seemed likely to become a pauper, and the skilled craftsman, who might prove a dangerous competitor for the custom of the townspeople, were refused admission. However, the wealthy merchant and the honest, non-enterprising laborer went unmolested. The initiative in these matters came generally from the Guilds and Companies which controlled the various trades carried on in the City. They were afraid of competition, and anxious to keep down the number of tradesmen among whom the available custom had to be divided. The chief principles which the Guilds had inherited from the Middle Ages were as follows; (i) all regulations affecting the trade were made by the Masters who ruled the Guild; (ii) no person could set up in business on his own unless he was a Master and had been admitted as such into the Guild, and (iii) the normal way of becoming a Master was by serving an apprenticeship of seven years under a Guildsman, and then

paying the fees for admission to the rank and privileges of Mastership. In this way, the trade was protected against an influx of inferior and irresponsible labor which might lower the standard of work, and, by competing for employment in the restricted market of the town, lower the level of the earnings of the craftsman.

Society in the reign of George II, however, was anything but medieval. Little was left of the elaborate system of industry based on the Guild. At the top of the industrial scale was a class of wealthy men, merchants or employers of labor, who had no patience with rules of this kind. They ran their business as they thought best, advanced boldly into any field that looked profitable, respecting the preserves of nobody, and they had no intention of teaching the secrets of their trade to any one except their own sons. At the other end of the scale were the laborers in common trades where the required degree of skill was small. Such men were not likely to go through a long period of apprenticeship when they could learn their job well enough without it, and nothing awaited them at the end of it but a fight for existence in an overstocked labor market in which they had no special advantage. Between these two classes came the highly skilled handicrafts, and there conditions were often quite different. As a long period of training was essential, apprenticeship had some meaning, and when it was over the craftsman was ready to start a business on his own. The Masters, in a trade of this kind, were in a commanding position. They had no employers over them with power to dictate terms; they had nothing to fear from the competition of upstart unqualified workmen; and they had a monopoly in training recruits to the craft. Whenever there were enough of them in a town to have an organization of their own they made strict rules for the training of novices and their admission to the status of Master, and no one who had not qualified according to these rules was permitted to open shop within the town.

The clockmakers of London were a trade of this kind. The company was not medieval in origin; it had been founded in 1631. But it was by nature suited to the medieval type of organization. The mathematical instrument makers were a branch of the Company of Clockmakers and followed the same rules. Watt, apparently, had not thought of this difficulty. His case was exactly that for which apprenticeship rules were designed. He wanted to be trained in order to become a Master and start a business on his own. His only proper course of action was to bind himself by a legal contract as an apprentice to a member of the trade. He was in no position, however, to conform to the ordin-

ary regulations. In the first place he was too old; in the second place he was a "foreigner" and had no right to work in the City; and in the third place he could not afford to undertake to serve the full term of seven years. He must find a Master who was prepared to break the rules. The fact that he was a foreigner who had no intention of setting up shop in the city was a point in his favor, for London was not afraid of possible rivals in Glasgow. To teach such a man the mysteries of the craft was a breach of the letter of the law only, not of the spirit of the law. It took Watt some three weeks to find Mr. John Morgan of Cornhill, a man who was willing to take him for a year and teach him all he wanted to learn. During that time Watt was to give his labor free, and as the engagement was quite irregular, he had to pay the large sum of twenty guineas to compensate his master for the trouble he was causing to his conscience.

Watt settled down to do the seven years of work in a single year. He put in ten hours of work a day, five days each week, but it was difficult to avoid wasting time. The workmen in the shop were specialists on some particular instrument; Watt wanted to learn to make them all, and so he worked with each in turn. But if the man he wanted happened to be busy, or away for a time, Watt was interrupted in his course of progress. In six weeks, however, he had outstripped a fellow-apprentice who had been in the shop for two years; in nine months he was as skillful as a fully trained and experienced workman, and could cover a wider field. All this time he hardly ever went out. When he finished work in the evening he was much too tired to think of amusements, and anyhow he could not afford them. But he had another reason for staying indoors. England was enjoying a short interval of peace, recovering from the strain of fighting with Austria against Prussia, before she embarked on a new war with Prussia against Austria. Some fifteen years before, to the strains of the popular new song, "Rule Brittania!" the British fleet had sailed out to defend their precious monopoly in the slave trade. Now, while the people of London were still proclaiming that "Britons never, never, never will be slaves," the officers of the Press-gang were lurking around the corner ready to pounce on any young Englishman who had faith in the freedom of his country as to walk the streets of the capital after dark. This was a serious danger to Watt, for, as he was a stranger with no rights in the City, he could not claim the protection of the civil authorities. In the spring of 1756, the Press-gang became very active. A fleet had to be manned in a hurry for Admiral Byng to take out, to disgrace itself at Minorca. It is believed that a thousand men were

taken in one night. “They now press anybody they can get,” Watt wrote to his father, “landsmen as well as seamen, except it be in the Liberties of the City, where they are obliged to carry them before my Lord Mayor first; and unless one be either ’prentice or a creditable tradesman, there is scarce any getting off again. And if I was carried before my Lord Mayor, I durst not avow that I wrought in the City, it being against their laws for any unfreeman to work, even as a journeyman, within the Liberties.” Fortunately, Watt escaped the clutches of the Press-gang.

All this time, Watt was working much too hard and not getting enough to eat. He cut his expenditure on food down to eight shillings a week, and could get it no lower without “pinching his belly.” The strain was too much for his fragile constitution. When his year was up his health gave way, and he suffered from violent attacks of rheumatism. He longed to get back to the fresh air of the Scottish countryside. In August 1756, he found the courage to face the weary journey, and mounting his horse, he turned his back on London. After a short stay at Greenock that restored his health and his spirits, he traveled on to Glasgow, with the outfit of tools bought in London, to offer his newly-won skill to the world. Watt, however, met with the same difficulties in Glasgow as he had faced in London. Here, too, he was a “foreigner,” and a dangerous “foreigner,” because he did not wish to only study the craft in the shop of a Master, but had every intention of setting up shop for himself. His trade came under the jurisdiction of the Incorporation of Hammermen, and its collection of industrial autocrats, worthy men, no doubt, but intellectually hammers indeed as compared with Watt’s gimlet. They refused him permission to work within the town in any capacity whatsoever. This was in spite of the fact that there was not one of them who pretended to understand the rudiments of his particular craft. Watt was saved by one of those odd coincidences that crop up from time to time in the ages of history. Within a month of his arrival in Glasgow, the University received a present of a case of astronomical instruments from Alexander Macfarlane, a merchant living in Jamaica. Classes in physical astronomy had recently commenced, and the gift was most opportune, but the sea voyage had thrown the delicate instruments out of gear, and they needed overhauling by an expert. Dr. Dick, in whose charge they were placed, remembered his young friend and asked him to undertake the work. Watt was delighted to have this chance of proving his skill, and soon put the whole collection into perfect order, for which service the University voted him the sum of five pounds. When, shortly afterwards,

it was learned that he had been refused leave to have a workshop in the town, the University took him under its protection and gave him a room within the walls of the College, where the writ of the Hammermen did not have jurisdiction.

This may have been the turning point in the life of James Watt. Watt was already a brilliant mechanic [6–10], but it is reasonable to assume that he would never have won fame as an engineer if he had not also become a great scientist. That side of his genius had hitherto been starved. In the University, he found himself for the first time in the society of men who were his equals in intellect and his superiors in scientific experience. Also, these men, being pioneers in an unconquered territory, had none of the pride that makes the professional refuse to associate with the amateur, nor did they, like some jealous guardians of accumulated knowledge, feel proprietary about their science and resentful against trespassers. It was as the mathematical instrument maker to the University of Glasgow that Watt gained admission to the precincts of the College in the summer of 1757, but as soon as his remarkable gifts were recognized, he was treated by both Professors and students as a friend and colleague rather than as an employee. The initial steps were made easy for him by the fact that he was already known personally to some of the University staff. Professor Muirhead, a relative of his mother, who had first introduced him to Dr. Dick was still there; and when Dick died, early in 1757, his successor as Professor of Natural Philosophy was a man named Anderson, the brother of one of Watt's school friends. Anderson was a young man, not more than eight years senior to Watt, and provided an excellent channel of approach to the keener scientists both of the older and the younger generation. Watt's workshop was in the inner court of the College and connected to the premises occupied by the Natural Philosophy department. Teachers and students would come into the workshop, as they were leaving or returning to their work, to consult him about some piece of apparatus or to give him an instrument to repair. His friends dropped in to chat with him and brought their friends. Before long they were discussing with him not only the intricacies of apparatus but the scientific problems on which they were engaged in research. Watt's workshop became the regular meeting-place for those who were doing original work and could accept criticism of the theories suggested to them by the results of their experiments. More than once a Professor received a valuable hint from some swift thought hatched in the brain of the young craftsman.

Of all the friends that Watt made at this time the two who most deeply influenced his future were Joseph Black and John Robison. Black was a scientific genius of the first order. He had that rare gift of imaginative insight that is not afraid to leap into a new world of speculation, finding, as it were by inspiration, a fresh significance in facts that have long been known to all. But he was not one to make wild guesses. “No man,” said Adam Smith, who knew him well, “has less nonsense in his head than Dr. Black,” and he combined this freedom of vision with an unrivalled lucidity of exposition and accuracy of experiment. Lord Brougham had heard him lecture and wrote of him, “I have heard the greatest understandings of the age giving forth their efforts in its most eloquent tongues, but I should, without hesitation, prefer, for mere intellectual gratification, to be once more allowed the privilege which I in those days enjoyed of being present while the first philosopher of his age was the historian of his own discoveries.” Black had come across Watt when he was at work on Macfarlane’s instruments. He would come and stand in the shop toying with a quadrant and whistling softly to himself. But it was not until later, when he had Watt make him some apparatus for his experiments, that he became aware of Watt’s genius. “I found him,” he says, “to be a young man possessing most uncommon talents for mechanical knowledge and practice, with an originality, readiness and copiousness of invention which often surprised and delighted me in our frequent conversations together.” The two men became close friends, and Black’s affection for Watt lasted to the end of his life. When he was an old man a friend brought him news of Watt’s triumph at law over an infringer of his patent. The old scientist, weakened by years of illness, wept with joy; and then apologized. “It is very foolish, but I can’t help it, when I hear of anything good to Jamie Watt.” Watt profited immeasurably from his contact with this inspiring mind, and was also kept in touch with the most advanced scientific thought of the day. He realized his debt to Black. “To him I owe,” he said, “in great measure my being what I am; he taught me to reason and experiment in natural philosophy, and was always a true friend and adviser.”

Robison was a younger man, who had just graduated when Watt arrived at the University. Though an able scientist, good enough to be elected Professor both in Glasgow and in Edinburgh, he was not the same caliber as Black. But he had great vitality and enthusiasm, qualities which made him an ideal companion for Watt when his bouts of ill-health made him talk of giving up work altogether. Robison quickly recognized that Watt was his superior, and

always generously admitted it. He has described his first conversation with Watt in his workshop in the College: “I saw a workman, and expected no more; but was surprised to find a philosopher, as young as myself, and always ready to instruct me. I had the vanity to think myself a pretty good proficient in my favorite study, and was rather mortified at finding Mr. Watt so much my superior.” They became friends, but Robison’s adventurous tastes carried him away to sea soon afterwards. Several years later he returned, and renewed his friendship with Watt. He found that, thanks to his more systematic training, he could help Watt by testing and analyzing “the random suggestions of his inquisitive and inventive mind.” But Watt was undoubtedly the leader, and was continually striking out into untrodden paths, where Robison was always obliged to be a follower. Watt had, by this time, gained a wide reputation. The young enthusiasts clustered round him. Whenever any puzzle came their way, they went to Watt. He needed only to be prompted; everything became to him the beginning of a new and serious study; everything became science in his hands.

Meanwhile Watt’s business was doing very well. The University, when granting him quarters, had not stipulated that he should work only for them. On the contrary, he was provided with a room fronting the street, where he could offer for sale to the public the instruments he made in his workshop. In order to develop this side of the business he went into partnership, in 1759, with a man named Craig, who undertook to provide most of the capital needed for expansion, and to do all the commercial transactions, which Watt, then as ever afterwards, detested. They started with stock and cash worth £200, and about five years later were making gross sales up to £600 a year, and kept a staff of sixteen men at work.

It was Watt’s reputation as a universal mechanical expert that brought so much custom to his shop. When anything had to be done and there was no one in Glasgow who knew how to do it – which was often – it was taken to Watt. He was always ready to try. If the instrument to be repaired was one that he had never seen before, he set to work to master its principles with what help he could find at the library, and was not satisfied until he had put it to rights. And what he learned he never forgot. In this way he repaired and afterwards made, fiddles, guitars, and flutes, although he could not tell one note of music from another. When a Masonic Lodge in Glasgow wanted an organ, the officers went to Watt. They imagined that Watt could do anything, and they asked him to build the organ. He sat down to study the theory of

music, thoroughly examined the mechanism of the best organ he could find, and devised an exact method by which he could tune the pipes by observing "the beats of imperfect consonances." By the time the work was completed, Watt had made substantial contributions, not only to the mechanics of organ design, but also to the theory of sound. Soon after he formed his partnership with Craig, Watt opened a shop in the town, though still living in the College. In 1763, at the age of 27, Watt became engaged to be married to his cousin, Margaret Miller, and so took a house, into which he moved in the following year. He was married in 1765 and had four children. Only two of the children survived their mother who died in childbirth in the fall of 1773. Watt then remarried in 1776. His second marriage was to Ann Macgregor, the daughter of a prosperous Glasgow merchant. There were two children to this marriage, Gregory and Janet, both of whom predeceased their father. Before both of his marriages, however, Watt had begun his pioneer work on the improved steam engine.

Review of Main Work on Mechanism Design

Although Watt had no formal study of mechanisms he became a highly gifted designer of mechanisms. The windmill flyball governor for regulating the gap between millstones was adapted by Watt as an engine speed regulator giving the first closed-loop servomechanism. Watt, instrument maker and engineer, was concerned with the synthesis of movement. Watt's rotative engine was the first engine to produce power directly on a shaft without the intervention of a water-wheel fed by a reciprocating pumping engine. He took out a patent in April 1784, which described various methods of converting angular motion into rectilinear motion. Of the methods described in this patent, the one that he developed was the parallel motion linkage.

Watt's linkage was a good solution to the practical problem. However, his solution did not satisfy mathematicians who knew that all four-bar straight-line linkages (that have no sliding pairs) can only trace an approximate straight line. An exact straight-line planar linkage was not known until much later, about 1864, when the French captain Charles-Nicholas Peaucellier finally synthesized the exact straight-line linkage that bears his name [11, 12]. The Peaucellier straight-line linkage is a more complex linkage than the four-bar and has eight members and six joints, four of which are ternary joints. Four-bar linkages were in widespread use by the sixteenth century, however,

they probably originated as early as the thirteenth century. Some drawings of that period indicate that a four-bar linkage was used in an up-and-down sawmill. Also, Leonardo da Vinci (1452–1519) described a crank and slider mechanism for a sawmill machine. The conversion of rotary to reciprocating motion (an oscillation through a small circular arc) using rigid links can be found in the sixteenth century. Although at that time the conversion of rotary to reciprocating motion was more frequently accomplished by cams and intermittent gearing. Nevertheless, the idea of linkages was a firmly established part of the repertory of the machine builder before 1600. In 1588, Agostino Ramelli published his book on machines where linkages were widely used [13]. The book exhibits more than 200 machines of various degrees of complexity and ingenuity. In reading this book, one might wonder if linkages had not reached their ultimate stage of development. However, it is important to note that there is a vast difference, both in conception and execution, between the linkages of Ramelli and those of Watt some 200 years later.

Designers of the four-bar linkage before Watt had confined their attention to the motions of the links attached to the frame (or ground). Watt, however, focused his attention on the motion of a point on the coupler link of the four-bar linkage. The year was 1784 and the application of this idea allowed Watt to build a double-acting steam engine. The earlier chain connecting piston and beam was now replaced by a linkage that was able to transmit force in two directions instead of only one. Watt had discovered coupler-point motion, although its definition in these terms lay well in the future. It was a singular achievement, one could almost say a pivotal point, along the road to kinematic synthesis. It took Watt several years to design the straight-line linkage that would change motion from straight-line to circular. In a letter to Matthew Boulton (a partner and machine builder who built engines in his works in Soho, a district of Birmingham, England) he wrote [7]: "I have got a glimpse of a method of causing a piston-rod to move up and down perpendicularly, by only fixing it to a piece of iron upon the beam, without chains, or perpendicular guides, or untowardly frictions, arch-heads, or other pieces of clumsiness … I have only tried it in a slight model yet, so cannot build upon it, though I think it a very probable thing to succeed, and one of the most ingenious simple pieces of mechanisms I have contrived, …" Watt was responsible for initiating profound changes in mechanical technology, but it should be recognized that the art of mechanics had, through centuries of slow development, reached the state where his genius could flourish. The know-

ledge and ability to provide the materials and tools necessary for Watt's research were at hand, and through the optimism and patient encouragement of his partner Boulton at the Soho Works, they were placed at his disposal.

The genius of Watt was nowhere more evident than in his synthesis of linkages [14]. An essential ingredient in the success of Watt's linkages, however, was his partner's appreciation of the entirely new order of refinement that the linkages required. Boulton, who had been a successful manufacturer of buttons and metal novelties long before his partnership with Watt was formed, had recognized at once the need for care in the building of Watt's steam engine. On February 7, 1769, he wrote to Watt, "I presumed that your engine would require money, very accurate workmanship and extensive correspondence to make it turn out to the best advantage and that the best means of keeping up the reputation and doing the invention justice would be to keep the executive part of it out of the hands of the multitude of empirical engineers, who from ignorance, want of experience and want of necessary convenience, would be very liable to produce bad and inaccurate workmanship; all of which deficiencies would affect the reputation of the invention." Boulton expected to build the engines in his shop "with as great a difference of accuracy as there is between the blacksmith and the mathematical instrument maker." The Soho Works solved the problem of producing the mechanisms (in sizes large enough to be useful in steam engines) that Watt devised [15]. The contributions of Boulton and Watt to practical mechanics cannot be overestimated. There were, in the eighteenth century, instrument makers and makers of timekeepers who had produced astonishingly accurate work, but such work comprised relatively small items, all being within the scope of a bench lathe, hand tools, and superb handwork. The rapid advancement of machine tools, which greatly expanded the scope of the machine- building art, began during the Boulton and Watt partnership from 1775 to 1800.

In April 1775 an event occurred that marked the beginning of a new era of technological advance. Boulton wrote to his partner and commented upon receiving the cast-iron steam engine cylinder that had been finished in Wilkinson's new boring mill: "it seems tolerably true, but is an inch thick and weighs about 10 cwt (approximately 1100 lbs). The diameter is about as much above 18 inches as the tin one was under, and therefore, it has become necessary to add a brass hoop to the piston, which is made almost two inches broad." This cylinder indeed marked the turning point in the discouragingly long development of the Watt steam engine, which for 10 years had occupied nearly

all of Watt's thoughts and all the time he could spare from the requirements of earning a living. Although there were many trials ahead for the firm of Boulton and Watt in further developing and perfecting the steam engine, the crucial problem of leakage of steam past the piston in the cylinder had now been solved by the boring mill. This tool was the first large machine tool capable of boring a cylinder both round and straight and the first of a new class of machine tools that, over the next 50 or 60 years, came to include nearly all of the basic types of heavy chip-removing tools that are in use today. The development of tools was accelerated by the inherent accuracy required of the linkages that were originated by Watt. Once it had been demonstrated that a large and complex machine, such as the steam engine, could be built sufficiently accurately so that its operation would be relatively free of trouble, many outstanding minds became engaged in the development of machines and tools. It is interesting, however, to see how Watt grappled with the solutions of problems that resulted from the advance of the steam engine.

During the 1770s the demand for continuous, dependable power applied to a rotating shaft was becoming insistent, and much of the efforts of Boulton and Watt was directed toward meeting this demand. Mills of all kinds used water or horses to turn "wheel-work," but, while these sources of power were adequate for small operations, the quantity of water available was often limited, and the use of enormous horse-whims was frequently impracticable. The only type of steam engine then in existence was the Newcomen beam engine, which had been introduced in 1712 by Thomas Newcomen. This type of engine was widely used, mostly for pumping water out of mines but occasionally for pumping water into a reservoir to supply a waterwheel. It was arranged with a vertical steam cylinder located beneath one end of a large pivoted working beam and a vertical plunger-type pump beneath the other end. Heavy, flat chains were secured to a sector at each end of the working beam and to the engine and pump piston rods in such a way that the rods were always tangent to a circle whose center was at the beam pivot. The weight of the reciprocating parts pulled the pump end of the beam down; the atmosphere, acting on the open top of the piston in the steam cylinder, caused the engine end of the beam to be pulled down when the steam beneath the piston was condensed. The chains would, of course, only transmit force from piston to beam when in tension.

A connecting rod, a crank, and a sufficiently heavy flywheel could have been used in a conventional Newcomen engine in order to supply power to a

rotating shaft, but contemporary evidence suggests that this solution was by no means obvious to Watt. At the time of his first engine patent, in 1769, Watt had devised a "steam wheel," or rotary engine, that used liquid mercury in the lower part of a toroidal chamber to provide a boundary for steam spaces successively formed by flap gates within the chamber. The practical difficulties of construction ruled out this solution to the problem of a rotating power source, but not until after considerable effort and money was spent on the idea. In 1777, a speaker before the Royal Society in London observed that in order to obtain rotary output from a reciprocating steam engine, a crank "naturally occurs in theory," but that in fact the crank is impractical because of the irregular rate of running of the engine and its variable length of stroke. He said that on the first variation of length of stroke the machine would be "either broken to pieces, or turned back." John Smeaton, in the front rank of English steam engineers of his time, was asked in 1781 by His Majesty's Victualling Office for his opinion as to whether a steam-powered grain mill ought to be driven by a crank or by a waterwheel supplied by a pump. His conclusion was that the crank was quite unsuited to a machine in which regularity of operation was a factor. "I apprehend," he wrote, "that no motion communicated from the reciprocating beam of a fire engine can ever act perfectly equal and steady in producing a circular motion, like the regular efflux of water in turning a waterwheel." He recommended, incidentally, that a Boulton and Watt steam engine be used to pump water to supply the waterwheel. Smeaton had thought of a flywheel, but he reasoned that a flywheel large enough to smooth out the halting, jerky operation of the steam engines that he had observed would be more of an encumbrance than a pump, reservoir, and waterwheel.

The simplicity of the eventual solution of the problem was not clear to Watt at this time. He was not, as tradition has it, blocked merely by the existence of a patent for a simple crank and thus forced to invent some other device as a substitute. Wasbrough, the engineer commonly credited with the crank patent, made no mention of a crank in his patent specification, but rather intended to make use of "racks with teeth," or "one or more pulleys, wheels, segments of wheels, to which are fastened rotchets and clicks or palls." He did, however, propose to "add a fly or flies, in order to render the motion more regular and uniform." Unfortunately, he submitted no drawings with his patent specification. James Pickard, a button maker in Birmingham, patented a counterweighted crank device in 1780 that was expected to remove the objection of a crank. The device operated with changing leverage and,

therefore, irregular power. The counterweighted wheel, revolving twice for each revolution of the crank, allowed the counterweight to descend while the crank passed the dead center position and would be raised while the crank had maximum leverage. No mention of a flywheel was made in this patent.

Wasbrough, finding that his "rotchets and clicks" did not serve, actually used a crank with a flywheel in 1780. Watt was aware of this, but he remained unconvinced of the superiority of the crank over other devices and did not immediately appreciate the regulating ability of a flywheel. In April 1781, Watt wrote to Boulton, "... I know from experiment that the other contrivance, which you saw me try, performs at least as well, and has in fact many advantages over the crank" [10]. The "other contrivance" probably was his swash wheel which he built and which appeared on his next important patent specification. Also in this patent were four other devices, one of which was easily recognizable as a crank, and two of which were eccentrics. The fourth device was the well-known sun-and-planet gearing. In spite of the similarity of the simple crank to the several variations devised by Watt, this patent drew no fire from Wasbrough or Pickard, perhaps because no reasonable person would contend that the crank itself was a patentable feature, or perhaps because the similarity was not at that time so obvious. However, Watt steered clear of directly discernible application of cranks because he preferred to avoid a suit that might overthrow his or other patents. For example, if the Wasbrough and Pickard patents had been voided, they would have become public property; and Watt feared that they might fall into the hands of men more ingenious, who would give Boulton and Watt more competition than Wasbrough and Pickard. The sun-and-planet arrangement, with gears of equal size, was adopted by Watt for nearly all the rotative engines that he built during the term of the "crank patents." This arrangement had the advantage of turning the flywheel through two revolutions during a single cycle of operation of the piston. This required a flywheel only one-fourth the size of the flywheel needed if a simple crank were used.

From the first, the rotative engines were made double-acting; i.e., work was done by steam alternately in each end of the cylinder. The double-acting engine, unlike the single-acting pumping engine, required a piston rod that would push as well as pull. It was in the solution of this problem that Watt's originality and sure judgment were most clearly demonstrated. A rack and sector arrangement was used on some engines. The first one, according to Watt, "has broke out several teeth of the rack, but works steady." A little later

he told a correspondent that his double-acting engine, "acts so powerfully that it has broken all its tackling repeatedly. We have now tamed it, however." It was about a year later that the straight-line linkage was thought out. "I have started a new hare," Watt wrote to his partner. "I have got a glimpse of a method of causing the piston-rod to move up and down perpendicularly, by only fixing it to a piece of iron upon the beam, without chains, or perpendicular guides, or untowardly frictions, archheads, or other pieces of clumsiness. I have only tried it in a slight model yet, so cannot build upon it, though I think it a very probable thing to succeed, and one of the most ingenious simple pieces of mechanism I have contrived."

This section is based on the tribute to James Watt by Eugene S. Ferguson, 1916–2004, a truly outstanding professional historian of technology whose detailed and insightful monograph [2] encouraged the author to attempt the writing of this brief article.

On the Circulation of Works

Watt's marvelously simple straight-line linkage was incorporated into a large beam engine almost immediately, and the inventor was elated when he told Boulton: "new central perpendicular motion answers beyond expectation, and does not make the shadow of a noise." The parallel motion linkage was included in an extensive patent submitted by Watt (British Patent 1321, 1782). Figure 2a is a drawing of the Watt engine. The engine had a 30-inch diameter cylinder and a stroke of 8 feet.

Figure 2a is Plate 15 in the book by J.P. Muirhead, *The Origin and Progress of the Mechanical Inventions of James Watt*, Vol. 3, London, England, 1854 [7]. A drawing of the Watt double acting steam engine that appeared in the work of Lardner [16] is reproduced here in Figure 2b.

Watt considered several alternative devices for the conversion of reciprocating motion to rotating motion in the steam engine. The device that he finally employed in the Watt and Boulton large beam engines is the sun-and-planet gearing that is shown in Figure 3.

Figure 3 is Plate 7 in the book by J.P. Muirhead, *The Origin and Progress of the Mechanical Inventions of James Watt*, Vol. 3, London, England, 1854 [7].

As brilliant as the conception of the parallel motion linkage was, it was followed up by a synthesis that is very little short of incredible. In order to

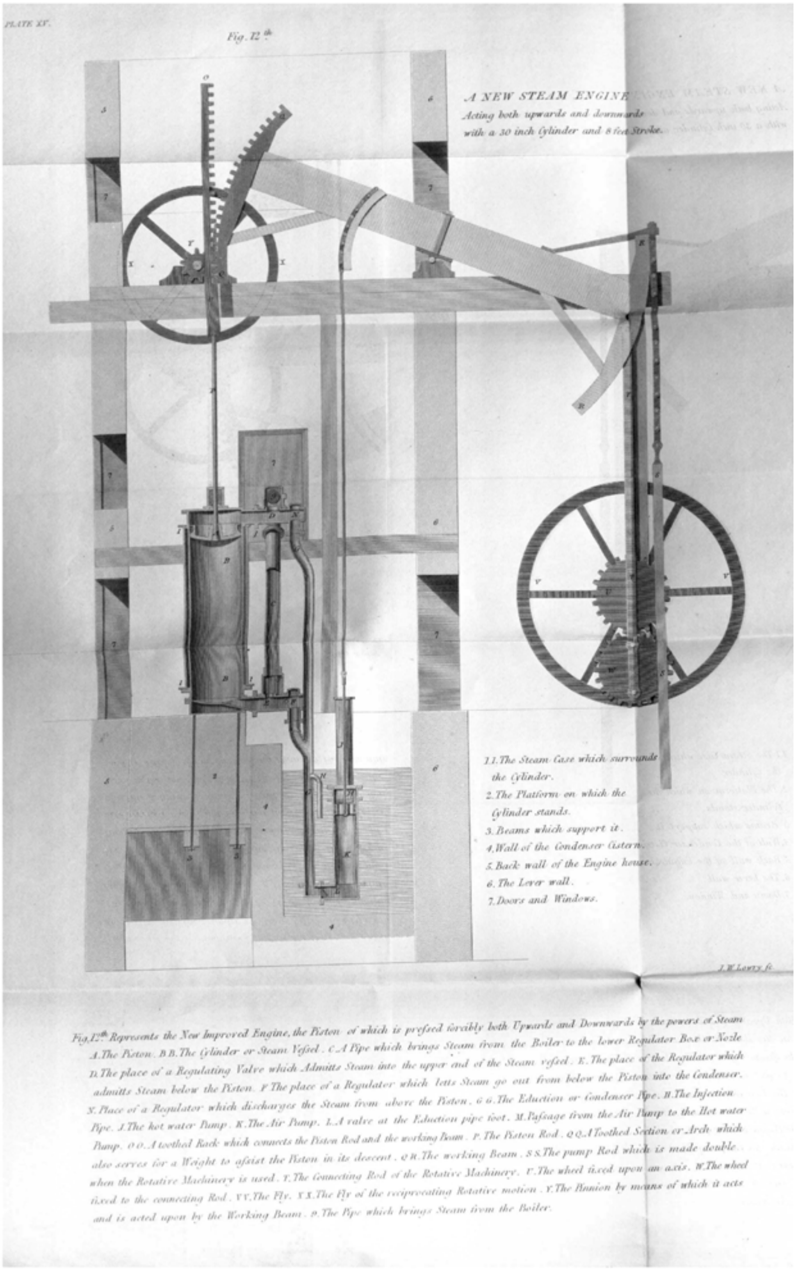

Fig. 2a. The Watt engine (British Patent 1321, March 12, 1782).

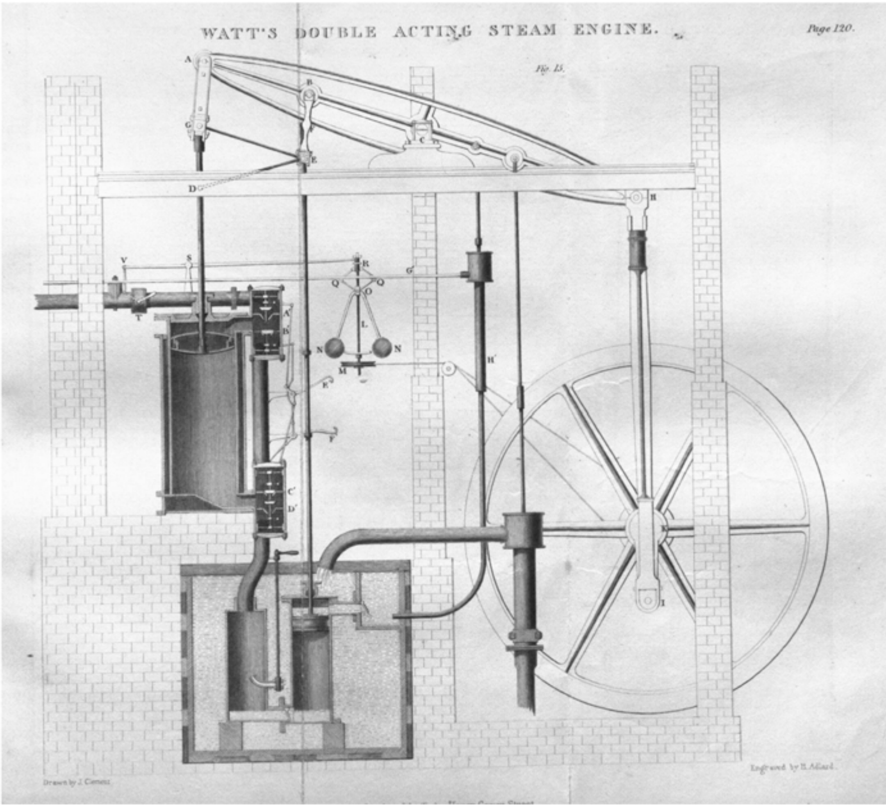

Fig. 2b. The Watt double acting steam engine.

make the linkage attached to the beam of his engines more compact, Watt plumbed the depths of his experience for ideas. This experience yielded up the work that was completed much earlier on a drafting machine that made use of a pantograph. Watt combined his straight-line linkage with a pantograph, one link becoming a member of the pantograph. This pantograph mechanism [16], denoted as ABEG, is shown in Figure 4.

With this design, the length of each oscillating link of the straight-line linkage was reduced to one-fourth instead of one-half the beam length. The entire mechanism could then be constructed so that it would not extend beyond the end of the working beam. This arrangement soon came to be known as Watt's parallel motion linkage, denoted as O_2ABO_4 in Figure 5.

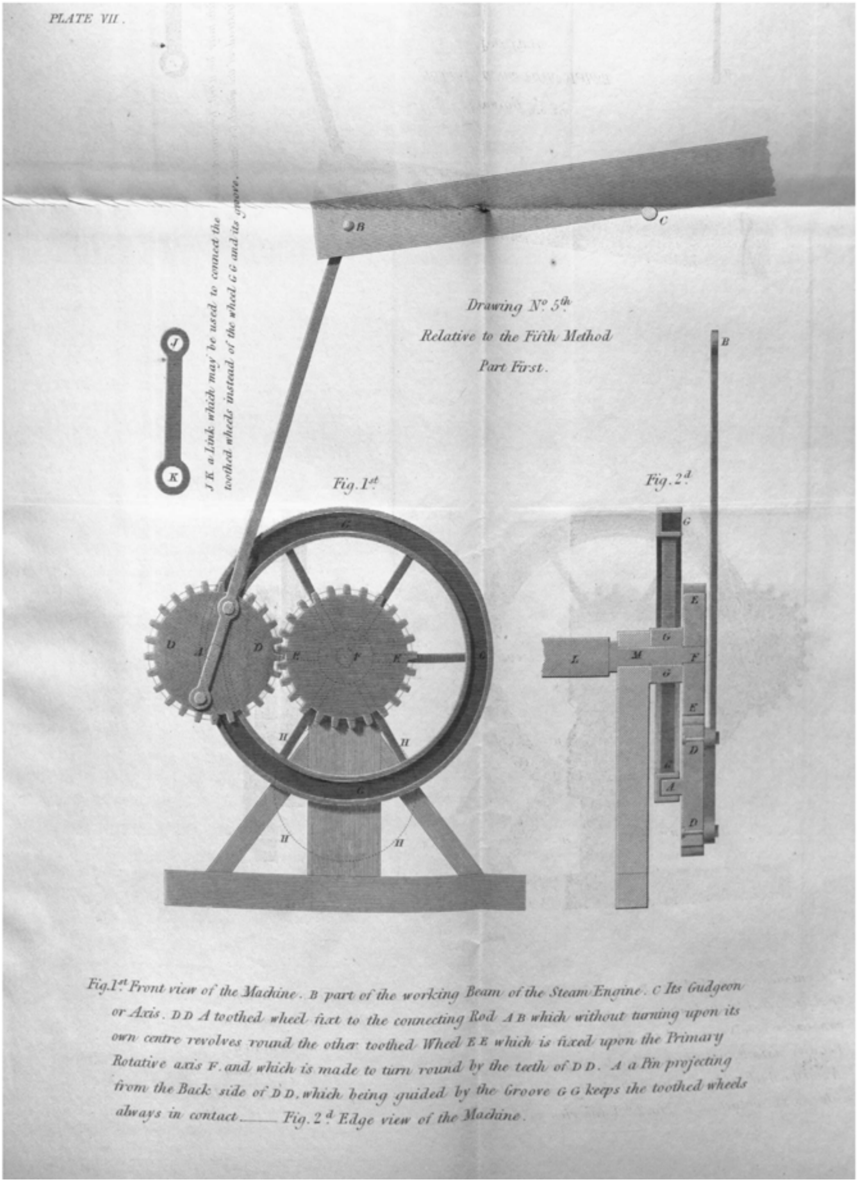

Fig. 3. The sun-and-planet gearing. (British Patent 1306, October 25, 1781).

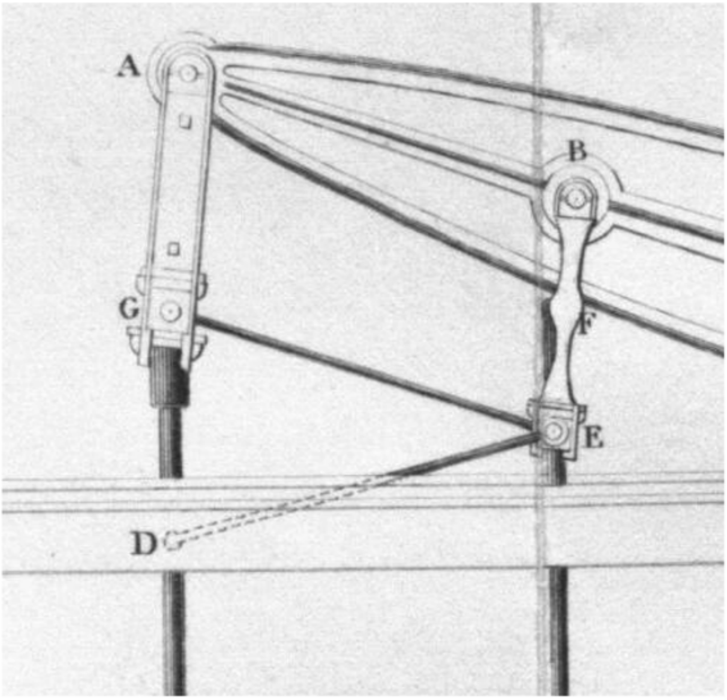

Fig. 4. The pantograph mechanism.

Through insight we can detect in this straight-line linkage the birth of a very ordered and advanced synthetic process. The kinematic analysis of the Watt four-bar linkage, see Figure 6a, and the geometry of the path of point M fixed in the coupler link AB (link 3) can be investigated using the method of kinematic coefficients [17].

The vectors that are required for the kinematic analysis of the Watt four-bar linkage are shown in Figure 6b.

Modern Interpretation of Main Contribution to Mechanism Design

The vector loop equation for the four-bar linkage can be written as

$$\overset{\surd \mathrm{I}}{\overline{R}_2} + \overset{\surd ?}{\overline{R}_3} - \overset{\surd ?}{\overline{R}_4} + \overset{\surd \surd}{\overline{R}_1} = 0, \tag{1}$$

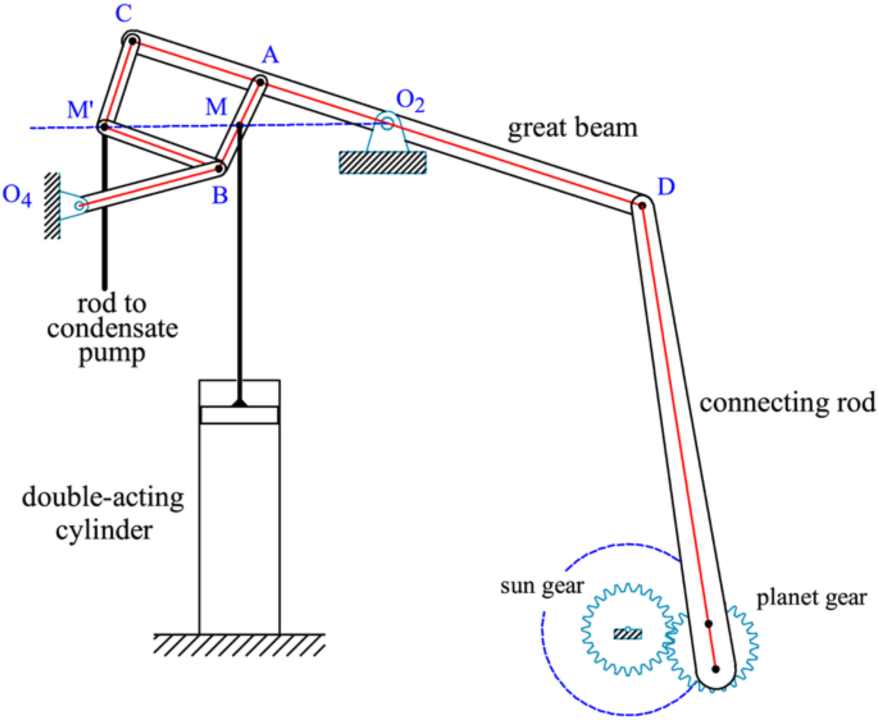

Fig. 5. The Watt parallel motion linkage.

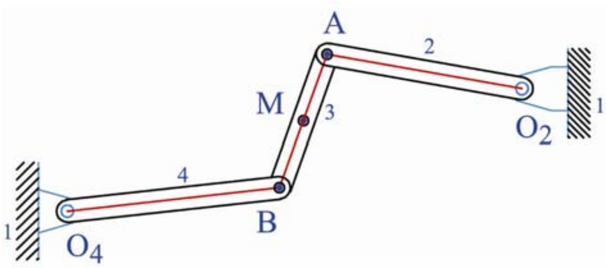

Fig. 6a. The Watt four-bar linkage.

where the first symbol above each vector indicates its magnitude and the second symbol indicates its direction. The known quantities are denoted by $\surd$ the unknown variables are denoted by ?, and the independent variable is denoted by I. Without loss in generality, the independent variable is assumed to be the angular position of link 2 and the unknown variables are the angular

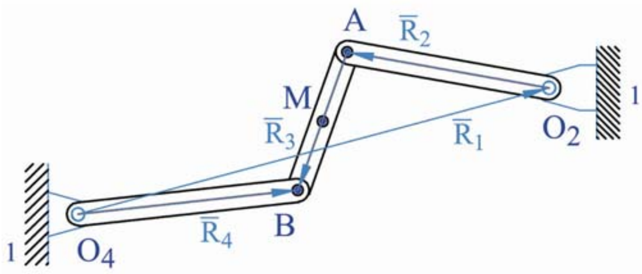

Fig. 6b. The vectors for the Watt four-bar linkage.

positions of the coupler link 3 and the side link 4. The X and Y components of Equation (1) are

$$R_2 \cos\theta_2 + R_3 \cos\theta_3 - R_4 \cos\theta_4 + R_1 \cos\theta_1 = 0 \tag{2a}$$

and

$$R_2 \sin\theta_2 + R_3 \sin\theta_3 - R_4 \sin\theta_4 + R_1 \sin\theta_1 = 0. \tag{2b}$$

Differentiating Equations (2) with respect to the independent variable θ_2 gives

$$-R_2 \sin\theta_2 - R_3 \sin\theta_3\theta_3' + R_4 \sin\theta_4\theta_4' = 0 \tag{3a}$$

and

$$R_2 \cos\theta_2 + R_3 \cos\theta_3\theta_3' - R_4 \cos\theta_4\theta_4' = 0, \tag{3b}$$

where $\theta_3' = \mathrm{d}\theta_3/\mathrm{d}\theta_2$ and $\theta_4' = \mathrm{d}\theta_4/\mathrm{d}\theta_2$ are referred to as the first-order kinematic coefficients of links 3 and link 4, respectively. Then writing Equations (3) in matrix form gives

$$\begin{bmatrix} -R_3 \sin\theta_3 & R_4 \sin\theta_4 \\ R_3 \cos\theta_3 & -R_4 \cos\theta_4 \end{bmatrix} \begin{bmatrix} \theta_3' \\ \theta_4' \end{bmatrix} = \begin{bmatrix} R_2 \sin\theta_2 \\ -R_2 \cos\theta_2 \end{bmatrix}. \tag{4}$$

The determinant of the coefficient matrix in Equation (4) can be written as

$$\mathrm{DET} = \begin{vmatrix} -R_3 \sin\theta_3 & R_4 \sin\theta_4 \\ R_3 \cos\theta_3 & -R_4 \cos\theta_4 \end{vmatrix} = R_3 R_4 \sin(\theta_3 - \theta_4). \tag{5a}$$

Note that the determinant is zero when

$$\theta_3 = \theta_4 \quad \text{or} \quad \theta_3 = \theta_4 + 180^\circ, \tag{5b}$$

i.e., the mechanism is in a special position (links 3 and 4 are either aligned or folded on top of each other). Using Cramer's Rule, the first-order kinematic coefficient of link 3, from Equation (4), can be written as

$$\theta_3' = \frac{\begin{vmatrix} R_2 \sin\theta_2 & R_4 \sin\theta_4 \\ -R_2 \cos\theta_2 & -R_4 \cos\theta_4 \end{vmatrix}}{\text{DET}} = \frac{R_2 R_4 \sin(\theta_4 - \theta_2)}{\text{DET}} \tag{6a}$$

and the first-order kinematic coefficient of link 4 can be written as

$$\theta_4' = \frac{\begin{vmatrix} -R_3 \sin\theta_3 & R_2 \sin\theta_2 \\ R_3 \cos\theta_3 & -R_2 \cos\theta_2 \end{vmatrix}}{\text{DET}} = \frac{R_2 R_3 \sin(\theta_3 - \theta_2)}{\text{DET}}, \tag{6b}$$

where the determinant is given by Equation (5a).

Differentiating Equations (3) with respect to the independent variable θ_2 gives

$$-R_2 \cos\theta_2 - R_3 \cos\theta_3 \theta_3'^2 - R_3 \sin\theta_3 \theta_3'' + R_4 \cos\theta_4 \theta_4'^2 + R_4 \sin\theta_4 \theta_4'' = 0 \tag{7a}$$

and

$$-R_2 \sin\theta_2 - R_3 \sin\theta_3 \theta_3'^2 + R_3 \cos\theta_3 \theta_3'' + R_4 \sin\theta_4 \theta_4'^2 - R_4 \cos\theta_4 \theta_4'' = 0, \tag{7b}$$

where $\theta_3'' = \mathrm{d}^2\theta_3/\mathrm{d}\theta_2^2$ and $\theta_4'' = \mathrm{d}^2\theta_4/\mathrm{d}\theta_2^2$ are referred to as the second-order kinematic coefficient of links 3 and 4, respectively. Then writing Equations (7) in matrix form gives

$$\begin{bmatrix} -R_3 \sin\theta_3 & R_4 \sin\theta_4 \\ R_3 \cos\theta_3 & -R_4 \cos\theta_4 \end{bmatrix} \begin{bmatrix} \theta_3' \\ \theta_4' \end{bmatrix} = \begin{bmatrix} R_2 \cos\theta_2 + R_3 \cos\theta_3 \theta_3'^2 - R_4 \cos\theta_4 \theta_4'^2 \\ R_2 \sin\theta_2 + R_3 \sin\theta_3 \theta_3'^2 - R_4 \sin\theta_4 \theta_4'^2 \end{bmatrix}. \tag{8}$$

Note that the coefficient matrices in Equations (4) and (8) must be the same, which is a useful check of the differentiation. Using Cramer's rule, the second-order kinematic coefficient of link 3, from Equation (8), is

$$\theta_3'' = \frac{\begin{vmatrix} R_2 \cos\theta_2 + R_3 \cos\theta_3 \theta_3'^2 - R_4 \cos\theta_4 \theta_4'^2 & R_4 \sin\theta_4 \\ R_2 \sin\theta_2 + R_3 \sin\theta_3 \theta_3'^2 - R_4 \sin\theta_4 \theta_4'^2 & -R_4 \cos\theta_4 \end{vmatrix}}{\text{DET}} \tag{9a}$$

and the second-order kinematic coefficient of link 4 is

$$\theta_4'' = \frac{\begin{vmatrix} -R_3 \sin\theta_3 & R_2 \cos\theta_2 + R_3 \cos\theta_3 \theta_3'^2 - R_4 \cos\theta_4 \theta_4'^2 \\ R_3 \cos\theta_3 & R_2 \sin\theta_2 + R_3 \sin\theta_3 \theta_3'^2 - R_4 \sin\theta_4 \theta_4'^2 \end{vmatrix}}{\text{DET}}, \tag{9b}$$

where the determinant is given by Equation (5a).

From the definition of the first-order kinematic coefficients, the angular velocities of links 3 and 4 can be written, respectively, as

$$\omega_3 = \theta_3' \omega_2 \quad \text{and} \quad \omega_4 = \theta_4' \omega_2. \tag{10}$$

Differentiating Equations (10) with respect to time, the angular accelerations of links 3 and 4 can be written, respectively, as

$$\alpha_3 = \theta_3'' \omega_2^2 + \theta_3' \alpha_2 \quad \text{and} \quad \alpha_4 = \theta_4'' \omega_2^2 + \theta_4' \alpha_2. \tag{11}$$

Now that the kinematic analysis of the linkage is complete, the kinematics of the coupler point M and the geometry of the path traced by point M can be investigated. The vectors that are required for the kinematic analysis of point M are as shown in Figure 7.

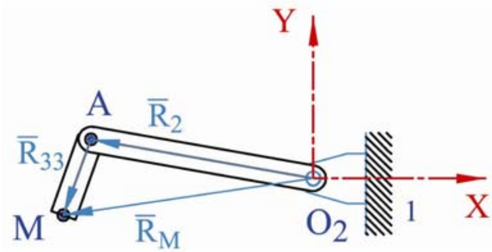

Fig. 7. The vectors for the coupler point M.

The vector equation for coupler point M can be written as

$$\bar{R}_M = \bar{R}_2 + \bar{R}_{33}. \tag{12}$$

The X and Y components of this equation are

$$X_M = R_2 \cos\theta_2 + R_{33} \cos\theta_3 \tag{13a}$$

and

$$Y_M = R_2 \sin\theta_2 + R_{33} \sin\theta_3. \tag{13b}$$

Differentiating Equations (13) with respect to the independent variable θ_2, the first-order kinematic coefficients of coupler point M are

$$X'_M = -R_2 \sin\theta_2 - R_{33} \sin\theta_3 \theta'_3 \tag{14a}$$

and

$$Y'_M = R_2 \cos\theta_2 + R_{33} \cos\theta_3 \theta'_3, \tag{14b}$$

where θ'_3 (i.e., the first-order kinematic coefficient of coupler link 3) is known from the kinematic analysis of the four-bar linkage, see Equation (6a).

Differentiating Equations (14) with respect to the independent variable θ_2, the second-order kinematic coefficients of coupler point M are

$$X''_M = -R_2 \cos\theta_2 - R_{33} \cos\theta_3 \theta'^2_3 - R_{33} \sin\theta_3 \theta''_3 \tag{15a}$$

and

$$Y''_M = -R_2 \sin\theta_2 - R_{33} \sin\theta_3 \theta'^2_3 + R_{33} \sin\theta_3 \theta''_3, \tag{15b}$$

where θ''_3 (i.e., the second-order kinematic coefficient of coupler link 3) is known from the kinematic analysis of the four-bar linkage, see Equation (9a).

The velocity and acceleration of coupler point M can be written, respectively, as

$$\bar{V}_M = (X'_M \hat{i} + Y'_M \hat{j})\omega_2 \tag{16a}$$

and

$$\bar{A}_M = (X''_M \hat{i} + Y''_M \hat{j})\omega_2^2 + (X'_M \hat{i} + Y'_M \hat{j})\alpha_2. \tag{16b}$$

The geometry of the path traced by coupler point M can be investigated as follows. The unit tangent vector and the unit normal vector to the path of point M can be written, respectively, as

$$\hat{u}_t = \frac{X'_M \hat{i} + Y'_M \hat{j}}{R'_M} \tag{17a}$$

and

$$\hat{u}_n = \hat{k} \times \hat{u}_t = \frac{-Y'_M \hat{i} + X'_M \hat{j}}{R'_M}, \tag{17b}$$

where

$$R'_M = \pm\sqrt{(X'_M)^2 + (Y'_M)^2}. \tag{18}$$

Sign Convention: The positive sign is used in Equation (18) if the change in the independent variable is positive (i.e., counterclockwise) and the negative sign is used if the change in the independent variable is negative (i.e., clockwise).

The radius of the curvature of the path traced by coupler point M can be written as

$$\rho_M = \frac{V_M^2}{A_M^n}, \tag{19a}$$

where the normal acceleration of coupler point M can be written as

$$A_M^n = \bar{A}_M \cdot \hat{u}_n. \tag{19b}$$

Substituting Equations (16b) and (17b) into Equation (19b) and performing the dot product, the normal acceleration of coupler point M can be written as

$$A_M^n = \frac{(X'_M Y''_M - Y'_M X''_M)\omega_2^2}{R'_M}. \tag{20}$$

Then substituting Equations (16a) and (20) into Equation (19a), and using Equation (18), the radius of the curvature of the path traced by the coupler point M can be written as

$$\rho_M = \frac{R'^3_M}{X'_M Y''_M - Y'_M X''_M}. \tag{21}$$

Finally, the Cartesian coordinates of the center of the curvature of the path traced by coupler point M can be written as

$$Xcc = X_M + \rho_M (u_n)_x \tag{22a}$$

and

$$Ycc = Y_M + \rho_M (u_n)_y. \tag{22a}$$

Substituting Equation (17b) into Equations (22), the Cartesian coordinates of the center of the curvature of the path traced by coupler point M can be written as

$$Xcc = X_M + \rho_M \left[\frac{-Y'_M}{R'_M} \right] \tag{23a}$$

and

$$Ycc = Y_M + \rho_M \left[\frac{X'_M}{R'_M} \right]. \tag{23b}$$

In general, an arbitrary coupler point of a general four-bar linkage will trace a curve which is described as a tricircular sextic [18–20]. However, coupler point M of the Watt four-bar linkage traces a special curve which is best described as a figure-eight-shaped curve, as shown in Figure 8.

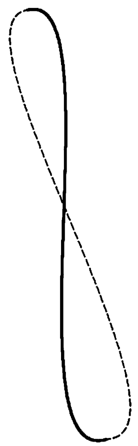

Fig. 8. The curve traced by coupler point M.

This curve is commonly referred to as a lemniscate and has two segments that approximate straight lines [21]. By means of the pantograph mechanism (see Figure 4), the path traced by point M' (see Figure 5) is similar to the path traced by coupler point M.

The Watt four-bar linkage was employed some 75 years after its inception by Richards when, in 1861, he designed his first high-speed engine indicator. The Richards indicator, which was introduced into England the following year, was an immediate success, and many thousands were sold over the next several decades. In considering the order of synthetic ability required to design the straight-line linkage and to combine it with a pantograph, it should be kept in mind that this was the first one of a long line of such mechanisms. Once the idea was abroad, it was only to be expected that many variations and alternative solutions should appear. One could wonder, however, what direction the subsequent work would have taken if Watt had not so clearly pointed the way.

Farey, in an exhaustive study of the steam engine, wrote perhaps the best contemporary view of Watt's work in 1827. As a young man, Farey had talked

several times with the aging Watt, and he had reflected upon the nature of the intellect that had caused Watt to be recognized as a genius, even within his own lifetime. In attempting to explain Watt's genius, Farey set down some observations that are pertinent not only to kinematic synthesis but to the currently fashionable term "creativity." In Farey's opinion, Watt's inventive faculty was far superior to that of any of his contemporaries; but his many and various ideas would have been of little use if he had not possessed a very high order of judgment, that "faculty of distinguishing between ideas; decomposing compound ideas into more simple elements; arranging them into classes, and comparing them together." Farey was of the opinion that while a mind like Watt's could produce brilliant new ideas, still the "common stock of ideas which are current amongst communities and professions, will generally prove to be of a better quality than the average of those new ideas, which can be produced by any individual from the operation of his own mind, without assistance from others." Farey concluded with the observation that "the most useful additions to that common stock, usually proceed from the individuals who are well acquainted with the whole series."

During most of the century after Watt had produced his parallel motion, the problem of devising a linkage, one point of which would describe a straight line, was one that engaged the minds of mathematicians, ingenious mechanics, and of gentlemanly dabblers in ideas. The quest for a straight-line mechanism more accurate than that of Watt far outlasted the pressing practical need for such a device. Large metal planning machines were well known by 1830, and by mid-century crossheads and crosshead guides were used on both sides of the Atlantic in engines with and without working beams. By 1819, Farey had observed quite accurately that, in England at least, many other schemes had been tried and found wanting and that "no methods have been found so good as the original engine; and we accordingly find, that all the most established and experienced manufacturers make engines which are not altered in any great feature from Mr. Watt's original engine."

Two mechanisms for producing a straight line were introduced before the Boulton and Watt monopoly ended in 1800. The first was by Cartwright (1743–1823), who is said to have had the original idea for a power loom. This geared device was characterized, somewhat patronizingly, by a contemporary American editor as possessing "as much merit as can possibly be attributed to a gentleman engaged in the pursuit of mechanical studies for his own amusement." However, only a few small engines were made under the patent. The

properties of a hypocycloid were recognized by White, an English engineer, in his geared design which employed a pivot located on the pitch circle of a spur gear revolving inside an internal gear. The diameter of the pitch circle of the spur gear was one-half that of the internal gear, with the result that the pivot, to which the piston rod was connected, traced out a diameter of the large pitch circle. White received a medal from Napoleon Bonaparte in 1801 for this invention when it was exhibited in Paris at an industrial exposition. Some steam engines employing White's mechanism were built, but without conspicuous commercial success. White himself agreed that while his invention was "allowed to possess curious properties, and to be a pretty thing, opinions do not all concur in declaring it, essentially and generally, a good thing."

The first of the non-Watt four-bar linkages appeared shortly after 1800. The origin of the grasshopper beam motion is somewhat obscure, although it came to be associated with Evans, the American pioneer, in the employment of high-pressure steam. A similar idea, employing an isosceles linkage, was patented in 1803 by Freemantle, an English watchmaker. This is the linkage that was attributed much later to Russell (1808–1882), the prominent naval architect. An inconclusive hint that Evans had devised his straight-line linkage by 1805 appeared in a plate illustrating his *Abortion of the Young Steam Engineer's Guide* (Philadelphia, 1805), and it was used on his Columbian engine, which was built before 1813. The Freemantle linkage, in modified form, appeared in Rees's *Cyclopaedia* of 1819, but it is doubtful whether even this would have been readily recognized as identical with the Evans linkage, because the connecting rod was at the opposite end of the working beam from the piston rod, in accordance with established usage, while in the Evans linkage the crank and connecting rod were at the same end of the beam. It is possible that Evans obtained his idea from an earlier English periodical, but concrete evidence appears to be lacking. If the idea did in fact originate with Evans, it is strange that he did not mention it in his patent claims, or in the descriptions that he published of his engines.

For more detailed information on the history of the problem to convert circular motion into straight line motion, the reader is referred to several references [see 22–24].

Concluding Remarks

James Watt died at Heathfield in Staffordshire on August 19th, 1819 and was buried in the grounds of St. Mary's Church, Handsworth, in Birmingham. He had been elected a Fellow of the Royal Society of Edinburgh in 1784, and a Fellow of the Royal Society of London in 1785. At the age of 70, he was granted the degree of LL.D. (Honorary Doctor of Law) by the University of Glasgow in 1806. Watt was made corresponding member of the Institute of France in 1808, and one of the eight Foreign Associates of the Academie des Sciences in 1814. He was offered a baronetcy, late in his life, but declined this honor. Perhaps this was evidence, to support his claim, that he was not over-anxious for fame. However, in spite of his humility, a marble monument to Watt was erected in Westminster Abbey, London, in 1824.

Watt, the man, can best be described by recounting the words of the famous Scottish novelist and poet, Sir Walter Scott (1771–1832) who wrote these words sometime after Watt's eightieth birthday: "The alert, kind, benevolent old man had his attention alive to every one's question. His information at every one's command – the man whose genius discovered the means of multiplying our national resources to a degree perhaps even beyond his own stupendous powers of calculation and combination. This potent commander of the elements, this abridger of time and space, this magician, whose cloudy machinery has produced a change on the world, the effects of which, extraordinary as they are, are perhaps only now beginning to be felt, was not only the most profound man of science, the most successful combiner of powers and calculator of numbers as adapted to practical purposes, was not only one of the most generally well-informed but one of the best and kindest of human beings."

To commemorate the bicentenary of the birth of Watt, the Institution of Mechanical Engineers of Great Britain decided to award every two years a Gold Medal to an engineer of any nationality who is deemed worthy of the highest award the Institution can bestow and that a mechanical engineer can receive. In making this award, the Institution sought the co-operation and advice of engineering Institutions and Societies in all parts of the world. In the long list of those who, by the practice of mechanical engineering, have added to the comfort, well-being and prosperity of mankind there is no man who holds a higher place in universal estimation than James Watt.

The eighth oldest higher education institution in the United Kingdom is the Heriot-Watt University. The history of this great university can be traced

back to the School of Arts of Edinburgh, which was founded in 1821 as the first mechanics institute in Great Britain. In 1852 the School incorporated the funds raised by public subscription to erect a monument to the memory of James Watt and was renamed the Watt Institution and School of Arts. In 1869, in response to a campaign by female subscribers and their supporters, the Governors took the radical step of allowing women to attend classes on equal terms with men. This placed the School in the vanguard of Scottish Higher Education Institutions. It was not until the Universities (Scotland) Act of 1889 that Universities were empowered to admit women to graduation.

In 1885, the School merged with the trust bequeathed to Edinburgh in 1623 by George Heriot, who had been a goldsmith and financier to King James VI (James I of England), and was renamed Heriot-Watt College. The first professors of the new technical college were appointed in 1887. In recognition of the teaching quality, the College became a Central Institution in 1902, partly funded by the Scottish Education Department. From 1928, an independent Board of Governors assumed responsibility for the College but continued to receive financial support from George Heriot's Trust. The College continued to enhance its reputation in the fields of science and engineering and, on the recommendation of the Royal Commission on Higher Education chaired by Lord Robbins, became Heriot-Watt University in 1966. In 1969, Midlothian Council gifted the University with the Riccarton estate in southwest Edinburgh. This provided the vital spring-board for Heriot-Watt University to expand on a new purpose-built campus and to develop leading-edge strengths in teaching and research. An integral part of the campus is Europe's first Research Park, founded in 1971. In 1998, the university merged with the Scottish College of Textiles to create the Scottish Borders Campus in Galashiels. Heriot-Watt University has a long tradition of innovative teaching, learning and research, geared to the needs of modern industry, business and society. The University specializes in the built environment, engineering and physical sciences, mathematics and informatics, computer science, business management, finance, languages and textiles. Today, the University is an internationally renowned center for innovative education, enterprise and cutting-edge research. With campuses in Scotland and Dubai and over 18,000 students registered on courses from over 153 countries worldwide, Heriot-Watt University can rightfully claim to be Scotland's international university.

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